Paper

CHERNOBYL ACCIDENT: RECONSTRUCTION OF THYROID DOSE FOR INHABITANTS OF THE REPUBLIC OF BELARUS

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Abstract—**The Chernobyl accident in April 1986 resulted in widespread contamination of the environment with radioactive materials, including ^{131}I and other radioiodines. This environmental contamination led to substantial radiation doses in the thyroids of many inhabitants of the Republic of Belarus. The reconstruction of thyroid doses received by Belarussians is based primarily on exposure rates measured against the neck of more than 200,000 people in the more contaminated territories; these measurements were carried out within a few weeks after the accident and before the decay of ^{131}I to negligible levels. Preliminary estimates of thyroid dose have been divided into 3 classes: Class 1 ("measured" doses), Class 2 (doses "derived by affinity"), and Class 3 ("empirically-derived" doses). Class 1 doses are estimated directly from the measured thyroidal ^{131}I content of the person considered, plus information on lifestyle and dietary habits. Such estimates are available for about 130,000 individuals from the contaminated areas of the Gomel and Mogilev Oblasts and from the city of Minsk. Maximum individual doses are estimated to range up to about 60 Gy. For every village with a sufficient number of residents with Class 1 doses, individual thyroid dose distributions are determined for several age groups and levels of milk consumption. These data are used to derive Class 2 thyroid dose estimates for unmeasured inhabitants of these villages. For any village where the number of residents with Class 1 thyroid doses is small or equal to zero, individual thyroid doses of Class 3 are derived from the relationship obtained between the mean adult thyroid dose and the deposition density of ^{131}I or ^{137}Cs in villages with Class 2 thyroid doses presenting characteristics similar to those of the village considered. In order to improve the reliability of the Class 3 thyroid doses, an extensive program of measurement of ^{129}I in soils is envisaged.**
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INTRODUCTION

As a result of the Chernobyl accident, over 20% (46,450 km^2) of Belarussian territory was contaminated with a ^{137}Cs level exceeding 37 kBq m^{-2} (1 Ci km^{-2}). In this contaminated area there are 27 cities and 2,736 villages with a population of over 2,000,000 people (Anonymous 1992). The measured activity ratios of ^{131}I-to-^{137}Cs ground deposition densities in the contaminated area ranged from approximately 1 to 100, the lower ratios being usually associated with the higher levels of ^{137}Cs (Dubina et al. 1990). The ^{131}I-ground-deposition density was higher than 0.26 MBq m^{-2} (7 Ci km^{-2}) in practically all of the villages located on the contaminated territory of Belarus. It is considered that this level of ^{131}I-ground-deposition density could lead to thyroid doses to infants of up to 2.5 Gy (Ilyin 1989).

Adequate estimates of individual thyroid exposures can be derived from results of large-scale monitoring of ^{131}I activity in human thyroids of the populations involved; this monitoring was carried out within a few weeks after the accident. Individual measurements of ^{131}I content in the thyroid of people who lived in the contaminated areas of Belarus, Russia, and Ukraine were ordered to be done urgently by the USSR Health Ministry on 29 April 1986. According to this order, all children whose thyroids had been exposed to doses of more than 1 Gy were to be placed under medical supervision, and children with thyroid doses greater than 2 Gy were to be examined in detail in medical clinics (Anonymous 1992).

A large number of radiation monitoring teams consisting of employees of sanitary and epidemiological stations, researchers from scientific institutes, and workers in civil defense, public health agencies, or other organizations took part in the large-scale monitoring of ^{131}I activity. Stationary and mobile teams were provided with available equipment, which was far from ideally suited to the task at hand. The equipment was used for measuring the level of gamma radiation near the thyroid gland for the purpose of determining the thyroid content of radioiodines, mainly ^{131}I, *in vivo*. In Belarus, more than 200,000 people were measured in this way within a few weeks after the accident.

Preliminary estimates of thyroid dose have been divided into three classes according to the methodology that was used.

Class 1 ("measured" doses)

Individual thyroid dose is calculated on the basis of one or more measurements of ^{131}I activity in the thyroid of the person considered. The Class 1 thyroid doses include only the doses due to the ^{131}I activity in the thyroid, as measurements were made after the short-lived radioiodines had decayed to insignificant levels. Thyroid doses from short-lived radioiodines and radiotelluriums would, in most cases, be small in comparison to the Class 1 doses and would be within the range of the uncertainty of the Class 1 dose estimates. For the sake of completeness thyroid doses from short-lived radioiodines and radiotelluriums will be added to the ^{131}I doses, when the Class 1 doses are revised in the years to come.

Class 2 (doses "derived by affinity")

For every village with a sufficient number of residents with Class 1 thyroid doses, individual thyroid dose distributions are determined for several age groups and several levels of milk consumption. This action has been called the "passportization" of the village with regard to thyroid exposure. The thyroid dose for any inhabitant from a village with "passportization" is derived by affinity with the Class 1 doses for individuals of the same age, taking into consideration the milk consumption rate and the length of time spent in the village after the accident. In the former Soviet Union, the Class 2 doses are called "passport doses." Contrary to the Class 1 thyroid doses, the Class 2 doses include the contribution resulting from the intake of short-lived radioiodines and radiotelluriums. Class 2 thyroid doses have also been estimated for children who were *in utero* at the time of the accident.

Class 3 ("empirically-derived" doses)

For any village where the number of residents with Class 1 doses is insufficient to determine meaningful thyroid dose distributions, the individual thyroid doses are inferred from the relationship obtained between the mean adult thyroid dose and the deposition density of ^{131}I or ^{137}Cs in villages with Class 1 doses presenting characteristics similar to those of the village considered. Just like the Class 1 thyroid doses, the Class 3 doses only include the contribution resulting from the intake of ^{131}I.

It is obvious that the uncertainties attached to Class 1 individual doses are lower than those for Class 2 or Class 3 doses, even if the direct thyroid measurements were done under poor conditions. Class 3 doses are the most uncertain.

The sharp increase in the number of childhood thyroid cancer cases that has occurred since the accident (Kazakov et al. 1992) stimulated the undertaking of epidemiological studies. In particular, an American-Belarussian case-control study was conducted between 1992 and 1995 (Astakhova et al. 1998), and a long-term American-Belarussian cohort study was started in 1994 (Wachholz 1994). Reliable information on individual thyroid doses is required.

The purposes of this paper are to (1) indicate how the initial assessment of the thyroid doses received by the inhabitants of Belarus has been conducted, (2) present the currently available results of the thyroid dose reconstruction effort, and (3) describe the refinements in the thyroid dose estimation planned for the near future.

Parts of the territories of Russia and Ukraine were also contaminated by radioiodines as a result of the Chernobyl accident. The thyroid dose reconstruction efforts that are carried out for the populations of those countries have been reported in several publications, for example by Likhtarev et al. (1996) for Ukraine and by Stepanenko et al. (1996) and Zvonova and Balonov (1993) for Russia. On average, the thyroid doses received by the most exposed populations are estimated to be about the same in Belarus and in Ukraine and to be somewhat lower in Russia. However, there is, to this date, no comprehensive review of the thyroid dose reconstruction efforts that have been undertaken in the three countries.

MATERIALS AND METHODS

The three methods of individual thyroid dose estimation will be discussed in turn.

Estimation of Class 1 individual thyroid doses ("measured" doses)

Estimation of Class 1 thyroid doses consists of three steps:

1. Measurement of the ^{131}I content in the thyroid of the individual considered;
2. Determination of the conditions of exposure to radioiodines; and
3. Determination of the contribution to the thyroid dose resulting from the intake of ^{131}I.

Measurement of the ^{131}I content in thyroids of Belarussian inhabitants. *In vivo* monitoring of ^{131}I thyroid content was carried out at a number of fixed locations in central hospitals of many raions# in Gomel and Mogilev Oblasts,** as well as in those of cities such as Minsk, Gomel, Mogilev, and Vitebsk; measurements were also made in sanatoria, rest houses, pioneer camps and in other facilities. In addition, mobile teams went to villages to monitor the thyroid glands of inhabitants. The personnel of these teams, with the exception of a few individuals, did not have adequate training to perform such measurements.

Because of the lack of special equipment for rapid monitoring of human thyroids, almost all thyroid measurements were done by means of very simple instruments with output in exposure or count rates. The DP-5, which has a Geiger-Müller counter as a detector, was used for about 80% of all measurements, while the

A raion is a political unit roughly equivalent to a county in the United States.

** An oblast is a political unit roughly equivalent to a state in the United States.

SRP-68-01 and the DRG3-02, which have NaI (Tl) scintillation detectors, were used for the remainder. All these instruments have analog outputs with 95% confidence intervals of no better than 30% for the DP-5 instrument and 10% for the SRP-68-01 and the DRG3-02 instruments. The minimum ^{131}I activity in the thyroid that could be detected varied according to the type of detector and to the measurement conditions. For the DP-5 instrument, the minimum detectable ^{131}I activity was about 50 kBq in field conditions, even though 5 kBq could be measured in laboratory conditions. For the SRP-68-01 instrument the corresponding numbers are 10 and 1 kBq, respectively. The calibration of the instruments was verified before and after the entire measurement campaign.

According to the instructions given to the monitoring teams, the subjects were to wash themselves before the measurements and to wear uncontaminated clothes. Two measurements were to be made for each subject: One against the thyroid and another, to take account of the background, against the liver. However, frequently the subjects did not wash themselves and/or wore contaminated clothes and the background measurement was not made against the liver. Also, the DP-5 instrument could be used under several conditions, and in many cases it is not clear if appropriate use was made or if the correct units of measurement were reported.

Assessment of conditions of exposure to radioiodines. The *in vivo* thyroid measurements give information related to the thyroid dose rate at the time of measurement. In order to reconstruct the individual thyroid doses, it is necessary to have information on the dynamics of intake of ^{131}I both before and after the *in vivo* thyroid measurement. However, only relative information is needed because the thyroid measurement provides a point of reference upon which the variation of activity in the thyroid can be anchored. It would have been desirable to obtain information on the dynamics of intake at the time when the individuals were measured. Unfortunately, this was not done, because priority was given to carrying out as many measurements as possible.

In order to obtain information on typical dynamics of intake of ^{131}I, personal interviewing of the population living in the contaminated areas of Belarus was organized in 1988. About 150,000 individuals, most of them evacuees or residents of the controlled areas of Gomel and Mogilev Oblasts, were interviewed. The interview form used included the following five questions (Gavrilin et al. 1989b):

1. Where did you live from 26 April 1986 through 31 May 1986? Indicate the dates of residence in each village.
2. What was the date when cows (goats) were put on pasture in your village in 1986? What was the origin of the fresh milk that you were drinking at that time?
3. What was the daily rate of your consumption of fresh milk between 26 April 1986 and 31 May 1986?
4. What was the date when you started taking potassium-iodide pills?
5. What was the date when you stopped consuming fresh milk?

Because of the rather long delay between the accident and the interviews, and because of the lack of experts to conduct the interviews, the quality of the answers is deemed to be relatively low. For the purpose of the initial assessment of Class 1 thyroid doses for individuals of a given village, the following interview results have been used: (1) The date when the village was evacuated (if appropriate), (2) the average date for the region when the cows (goats) were first put on pasture in 1986, and (3) the date when the consumption of fresh cow's milk of local origin was stopped. Available information on the date when individuals started taking potassium-iodide pills was not used either because the date given was too late to have a significant effect on the thyroid dose estimate or because the answers provided were thought not to be reliable. Finally, information on the daily consumption of fresh milk is not necessary in the initial assessment of the Class 1 thyroid doses, as long as it remained relatively constant during the time of exposure.

Determination of the thyroid dose on the basis of results of *in vivo* thyroid measurements and personal interviews. The primary features of thyroid dose reconstruction on the basis of *in vivo* thyroid measurements are described in Russian publications issued in the late 1980's (Arefieva et al. 1987, 1988).

In the initial assessment it is assumed that, at the time of measurement, t_m, counted from the occurrence of fallout resulting from the accident, only ^{131}I is present in the thyroid. This is justified because most of the measurements were conducted at least 8 d after the accident, when short-lived radioiodines had substantially decayed. The ^{131}I activity $G(t_m,i)$ in the thyroid gland of an individual of age i at the time of measurement is calculated according to the formula

$$G(t_m, i) = k(i) \times [P_{th}(t_m) - P_b(t_m)], \qquad (1)$$

where

$k(i)$ = A calibration coefficient relating the ^{131}I activity in the thyroid to the indication of the measuring instrument, Bq h μR^{-1} or Bq h mR^{-1}; the value of $k(i)$ depends on the mass of the thyroid, which varies according to the age i of the measured individual;

$P_{th}(t_m)$ = The exposure rate measured near the thyroid, μR h^{-1} or mR h^{-1}; and

$P_b(t_m)$ = The "background" exposure rate including that due to contaminated clothing, activity deposited on the ground, etc., μR h^{-1} or mR h^{-1}.

On the basis of the measured ^{131}I activity in the thyroid, $G(t_m,i)$, it is possible to estimate the thyroid dose, $D_0(t_m, i)$, from the time of measurement to infinity, assuming that there was no further radioiodine intake after the measurement. The value of $D_0(t_m,i)$ is determined with relatively low uncertainty:

$$D_0(t_m, i) = d(i) \times G(t_m, i), \tag{2}$$

where $d(i)$ is an age-dependent coefficient, Gy Bq^{-1}.

In order to calculate the thyroid dose, $D_{131}(i,k)$, resulting from environmental contamination by ^{131}I, it is assumed in the initial assessment that there was a single occurrence of fallout at a time that varies according to the region considered. The thyroid dose, $D_{131}(i,k)$, from ^{131}I intake can be written as

$$D_{131}(i, k) = f(t_m, i, k) \times D_0(t_m, i), \tag{3}$$

where $f(t_m,i,k)$ is a function that represents the variation of ^{131}I activity in the thyroid both before and after the measurement; this function depends on the time, t_m, elapsed between the occurrence of fallout and the time of measurement, on the age i of the individual, and on the mode k of ^{131}I intake.

For the initial dose assessment, only two modes of ^{131}I intake are considered: inhalation during cloud passage and ingestion of fresh milk. However, in villages, because large amounts of fresh milk of local origin are consumed, a very small fraction of the dose was due to inhalation of ^{131}I during cloud passage. In the initial assessment, inhalation of ^{131}I was ignored for the populations of villages and only taken into account for the populations of cities.

Standard models of environmental transfer and human intake of ^{131}I were used to calculate the values of $f(t_m,i,k)$ for each of the two modes of intake (Arefieva et al. 1987, 1988). The main assumptions were as follows:

1. Both cloud passage and fallout were instantaneous and occurred only once;
2. Cows had been put on pasture before fallout occurred;
3. The effective clearance rate of ^{131}I from pasture is $0.15\ d^{-1}$;
4. The effective clearance rate of ^{131}I from cow's milk is $0.63\ d^{-1}$;
5. The individual consumes fresh milk of the same origin and at the same rate during the entire contamination period; modifications to the calculations can be made if the personal interview reveals that this assumption is not correct;
6. The effective clearance rate of ^{131}I from the human thyroid varies from $0.116\ d^{-1}$ for an infant to $0.092\ d^{-1}$ for an adult; and
7. The intake of potassium-iodide pills, if any, occurred too late to be effective in blocking the uptake of ^{131}I by the thyroid.

As an example, Fig. 1 illustrates the relative importance of the values of $f(t_m,i,k)$ for the two modes of ^{131}I intake for infants (less than 1 y old) as a function of the time of measurement, t_m.

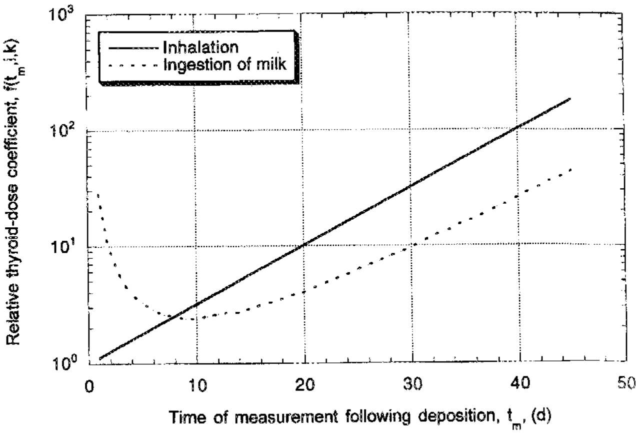

Fig. 1. Variation, vs. time t_m counted from the date of ^{131}I single fallout deposition to the date of thyroid measurement, of the ratio $f(t_m,i,k)$ of the thyroid dose resulting from the single fallout deposition and of the thyroid dose calculated from the time of thyroid measurement to infinity, assuming no further intake after the measurement. The curves are for inhalation ($k = 1$) and ingestion of milk ($k = 2$) by a 3-month-old baby (age i).

Estimation of the Class 2 thyroid doses (doses "derived by affinity")

Estimation of the Class 2 thyroid doses consists of two steps:

1. Statistical analysis of the Class 1 thyroid doses in order to derive estimates of the contribution of ^{131}I to the thyroid dose, taking into account the level of milk consumption; and
2. Determination of the thyroid dose resulting from the intake of all radioiodines.

A detailed description of the methodology used to estimate Class 2 thyroid doses for a number of villages of Belarus is provided in Gavrilin et al. (1991a).

Estimation of the contribution of ^{131}I to the thyroid doses. For a given village, the estimation of the contribution of ^{131}I to the Class 2 thyroid dose depends on the number, n, of Class 1 individual dose estimates for children (up to 18 y old) and for adults (older than 18 y) of the village:

- If the number, n, for a particular village is greater than 24, the arithmetic mean, D_m, and the arithmetic standard deviation, σ, were calculated on the basis of the distribution of the individual dose estimates in that village;
- If n is less than 25 but greater than 10, only the parameter D_m was estimated and the value of σ was assigned according to appropriate available values for neighboring villages. These criteria were applied separately to the sets of thyroid dose estimates for children and adults; and
- If n is equal to or less than 10, thyroid dose estimates for adults and children were combined after the dose estimates had been recalculated to

take into account the differences in thyroid dose coefficients and in milk consumption and breathing rates for children and adults. In a number of cases, for the purpose of increasing the number of usable Class 1 dose estimates, villages from the same area with similar levels of ^{137}Cs ground deposition density were combined.

All Class 2 thyroid dose estimates have been divided into distinct categories of reliability according to the method of calculation for children and adults: From the highest (for $n>25$ separately for children and adults in the village) to the lowest (for the case where villages were combined).

Each set of Class 2 thyroid dose estimates for the population of a village is presented in the form of a table containing the values of geometric mean and geometric standard deviation of the individual dose distributions related to 19 age groups and to a range of consumption rates of locally produced milk, including default values in case of unknown milk consumption rate. The values of geometric mean and geometric standard deviation were calculated on the basis of the values of arithmetic mean (D_m) and of arithmetic standard deviation (σ). Those parameters were derived from the distribution of the milk consumption rates for each age group, as they were obtained in the personal interviews. There are 19 age groups (18 age groups for children up to 18 y and a group for adults); the levels of milk consumption rate that are considered range from 0 L d^{-1} (solely inhalation) to 4.0 L d^{-1}.

The preliminary analysis of the answers of the Belarussian rural inhabitants regarding the values of their milk consumption rates in April–May 1986 gave the opportunity to estimate numerically the rates for each age group. The distribution of individual milk consumption rate (except for the individuals who did not drink milk at all) was described by a lognormal function with a geometric standard deviation of 1.6 ± 0.1 for each age group. The values of the geometric means of the milk consumption rates for different age groups, which were used for "passportization," are presented in Table 1. It can be seen from Table 1 that the average milk consumption rate increases with age. Thus, the trend of milk consumption rate with age in Belarus appears inverse to that in the U.S. (Dreicer et al. 1990). However, comparison of the average thyroid dose estimates for children and adults, calculated on the basis of direct thyroid measurements, implies that the milk consumption rates for children and adults are equal. Thus, further investigation will be needed to determine if the data in Table 1 are indeed representative.

Table 1. Characteristics of milk consumption rate of Belarus residents as determined by personal interviews in 1988. The estimates are relevant to rural inhabitants of the Mogilev and Gomel Oblasts during April–May 1986.

Year of birth	Number of people	Geometric mean (L d^{-1})	Geometric standard deviation
1986–1973	743	0.4	1.6
1972–1970	174	0.5	1.6
≤1969	1,080	0.7	1.6

The individual thyroid doses, $D_{131}(i)$, are calculated as the sum of the dose from inhalation, $D_{131}(i,h)$, and the dose from ingestion of milk, $D_{131}(i,g)$:

$$D_{131}(i) = D_{131}(i, h) + D_{131}(i, g). \qquad (4)$$

The arithmetic mean value of the individual inhalation doses for adults, $\bar{D}_{131}(a,h)$, is assumed to be a fraction $p(a)$ of the arithmetic mean value of the individual ingestion doses for adults, $\bar{D}_{131}(a,g)$:

$$\bar{D}_{131}(a, h) = p(a) \times \bar{D}_{131}(a, g). \qquad (5)$$

On the basis of the experience from nuclear weapons tests and from measurements related to the Chernobyl accident (Ng et al. 1990; UNSCEAR 1988), the value of $p(a)$ is taken to be equal to 0.05 for all villages where inhabitants consumed locally produced milk without any interruption. The inhalation doses for other age categories are derived from the value of $\bar{D}_{131}(a,h)$, taking into account the differences in breathing rates and in thyroid doses per unit intake.

Determination of the thyroid dose resulting from the intake of all radioiodines and radiotelluriums. There is evidence that the thyroid cancer risk coefficient resulting from internal irradiation of the thyroid is higher for short-lived radioiodines (^{132}I to ^{135}I) than for ^{131}I (Goslings 1989; Vasilenko et al. 1970). It is therefore important to take into account the level of thyroid exposure from isotopes ^{132}I to ^{135}I, even if their dose contributions are much smaller than that from ^{131}I. Total thyroid dose, including that due to incorporated short-lived nuclides of tellurium and iodine, can be expressed as

$$D_{\Sigma}(i) = S(t_e, i, k) \times D_{131}(i), \qquad (6)$$

where $S(t_e,i,k)$, which is the ratio of the total dose from all isotopes of iodine and tellurium to the dose from ^{131}I only, is a function that depends on the duration of exposure, t_e, on the age of the individual, i, and on the mode of intake, k, of radioiodines and radiotelluriums.

Calculation of the possible values of $S(t_e,i,k)$ has been done separately for different age groups, considering the intake of the relevant isotopes of iodine (^{131}I to ^{135}I) and of tellurium (^{131}Te to ^{135}Te, ^{131m}Te, ^{133m}Te). It can be assumed that there was no fractionation among the isotopes of the same element, so that the ratio of their activities was solely dependent upon radioactive decay. The values of the ratios of radioisotope activities of the same element were estimated in accord with the data of Kolobashkin et al. (1983). However, fractionation between iodine and tellurium should be taken into account for isotopes of tellurium. The ratios of the ground deposited activities of ^{132}Te and ^{131}I in the contaminated areas of Gomel and Mogilev Oblasts were taken to be in the range of 0.7 to 1.0 on the basis of available results of measurements in environmental samples (Izrael et al. 1990; Makhon'ko et al. 1996).

The intake of radionuclides by inhalation and by ingestion of fresh milk has been taken into consideration. It was assumed that milk was drunk twice a day. Three values of time duration of radionuclide intake, t_e, have been considered: (1) during the first day after the accident, (2) during the first eight days after the accident (typical for evacuated people), and (3) during the first fifteen days. Estimates of values of the coefficient $S(t_e,i,k)$ that were used for the initial assessment are presented in Table 2 for the two modes of intake (inhalation and ingestion of fresh milk) and for the three time durations. Most of the values of $S(t_e,i,k)$ are in the range from 1.0 to 1.2. As expected, the values of $S(t_e,i,k)$ are greater for inhalation than for ingestion and for short intakes immediately after the accident. A maximum value of $S(t_e,i,k) = 1.5$ has been calculated for the hypothetical case of an inhalation intake by a 3-mo-old baby during the first day of environmental contamination and no later exposure to Chernobyl-derived activity.

For the initial assessment of Class 2 thyroid doses, age-dependent inhalation and ingestion dose factors for radioiodines (^{131}I to ^{135}I) have been taken from ICRP Publication 56 (ICRP 1990). Dose factors for radioisotopes of tellurium have been calculated using the model described in ICRP Publication 30 (ICRP 1979) for tellurium and the model described in ICRP Publication 56 (ICRP 1990) for their radioiodine decay products.

Estimation of fetal thyroid doses. For pregnant women exposed to radioiodines from the Chernobyl accident, the thyroid dose to the fetus also needs to be considered. The thyroid dose to the fetus, $D_{131}[(t_p,f,k)$, from ^{131}I was estimated as a fraction of the mother's thyroid dose $D_{131}(t_p,m,k)$ (Arefieva et al. 1987; Simon et al. 1990). The formula for estimating the total thyroid dose for the fetus, $D_\Sigma(t_p,f,k)$, including short-lived radioiodines, is

$$D_\Sigma(t_p, f, k) = S_f(t_p, f, k) \times D_{131}(t_p, f, k)$$
$$= S_f(t_p, f, k) \times \eta_{131}(t_p) \times D_{131}(t_p, m, k), \quad (7)$$

where $S_f(t_p,f,k)$ = ratio of the thyroid dose from all radioiodines to that from ^{131}I alone for the fetus; and $\eta_{131}(t_p)$ = ratio of the fetal ^{131}I thyroid dose to that of the mother's ^{131}I thyroid dose; the value depends upon the time of pregnancy t_p.

The values of $S_f(t_p,f,k)$ were assessed on the basis of the data of Simon et al. (1990). The values of $\eta_{131}(t_p)$ and $S_f(t_p,f,k)$ assumed in the initial assessment are shown in Table 3.

Table 2. Estimated values of the ratio of the total thyroid dose from all radioiodines and ^{132}Te to that from ^{131}I only [coefficient $S(t_e,i,k)$] for two modes of intake (inhalation and ingestion) and for three durations of exposure (the first day after the accident, the first eight days after the accident, and the first fifteen days after the accident) in the vicinity of the reactor. The ranges represent variations according to the age of the individual (from newborn to adult).

	Duration of intake immediately after the accident		
Pathway	First day	First eight days	First fifteen days
Inhalation	1.3–1.5	1.1–1.2	1.1–1.2
Ingestion	1.1–1.2	1.04–1.07	1.03–1.04

Estimation of Class 3 thyroid doses ("empirically-derived" doses)

In the majority of villages in Belarus, the number of Class 1 thyroid dose estimates is very small or equal to zero. Under those conditions, Class 2 doses cannot be estimated. Although the ^{131}I ground deposition densities are available for a number of villages, the only environmental radiation measurement that is consistently available is the ground deposition density of ^{137}Cs. The thyroid dose received by people for whom there is no opportunity to obtain Class 1 or Class 2 dose estimates has been derived from the empirical relationship determined between the Class 1 thyroid doses and the ground deposition density of ^{137}Cs in villages with a sufficient number of *in vivo* thyroid measurements. Such thyroid dose estimates are denoted as Class 3 data. The Class 3 thyroid doses include only the contribution from the intake of ^{131}I.

More specifically, the analysis was based

1. On individual Class 1 thyroid dose estimates for adults, because the dose estimates for adults show less variability than the dose estimates for children. The estimate of arithmetic mean thyroid dose for adults in each village containing at least 25 Class 1 dose estimates for adults (248 villages in Gomel and Mogilev Oblasts in Belarus as well as 70 villages in Kaluga Oblast and 20 villages in Bryansk and Tula Oblasts in Russia) were included in the analysis; and
2. On official data of ^{137}Cs ground deposition density in the villages of interest; such data have been published by the State Committee of Hydrometeorology (1989). Also, available data of the ratio of the ^{131}I:^{137}Cs deposition densities in the villages were taken into account.

As the result of the analysis, a semi-empirical formula is suggested for a number of specific areas (Gavrilin et al. 1996b). On one hand, the size of such areas should be large enough to encompass the main variants of the Chernobyl fallout, including wet and dry deposition from the same effective radioactive cloud. On the other hand, the size of the area should be small enough to avoid substantial influence of the variability of radioactive air concentration in the cloud on the arithmetic mean thyroid dose for the inhabitants of one age group in the village located within the area. For the initial assessment, every administrative raion of the entire territory of Belarus (except for those raions inside the 30-km zone) was considered to be such an area. For the raions inside the 30-km zone, such areas could be much smaller (for example, a group of villages).

Table 3. Values of the ratio $\eta_{131}(t_p)$ of the fetal ^{131}I-thyroid dose to that of the mother's ^{131}I thyroid dose, and of the ratio $S_f(t_p,f,k)$ of the thyroid dose from all radioiodines to that for ^{131}I for the fetus.

End of the current month of pregnancy	<3	3	4	5	6	7	8	9
$\eta_{131}(t_p)$	0	0.2	0.7	1.2	2.4	1.4	1.2	1.1
$S_f(t_p,f,k)^a$								
inhalation	—	1.8	1.4	1.4	1.4	1.3	1.3	1.3
ingestion	—	1.4	1.2	1.2	1.2	1.2	1.2	1.1

[a] The values of $S_f(t_p,f,k)$ correspond to an intake of radioiodines limited to the first day after the accident. They would be lower in most other scenarios.

Eqn (8) provides the relationship that was used to estimate the thyroid doses received by people in a given age class on the basis of ground deposition densities in the area considered (Tsyb et al. 1994):

$$D(i,j,x) = c_0 \times R(x) \times q(x) \times \left[1 + d_0 \times \frac{R(j,x)}{R(x)} \times \frac{q(j,x)}{q(x)}\right] \times \frac{K_i}{K_j}, \quad (8)$$

where

$D(i,j,x)$ = Arithmetic mean thyroid dose from ^{131}I for individual in age class i in village j in the area x, Gy;
c_0 = Empirically-derived coefficient for adult thyroid dose calculation, 3.3×10^{-8} Gy m^2 Bq^{-1};
$R(x)$ = Average ratio of the ^{131}I:^{137}Cs ground deposition density in area x, dimensionless;
$q(x)$ = Average ^{137}Cs ground deposition density in area x, Bq m^{-2};
d_0 = A unitless coefficient equal to 0.4;
$R(j,x)$ = Ratio of the ^{131}I:^{137}Cs ground deposition density in village j in area x, dimensionless;
$q(j,x)$ = ^{137}Cs ground deposition density in village j in area x, Bq m^{-2};
K_i = Coefficient relating the average thyroid dose for children in age class i to the average thyroid dose for adults, dimensionless; and
K_j = Coefficient relating possible differences in lifestyles in village j compared to those in the reference areas, such as differences in dates of evacuation or in the dates of the beginning of pasture season for cows.

In eqn (8), values of parameters c_0 and d_0 are the same for all territories and were estimated on the basis of data for two reference areas: (1) The part of Hoiniki Raion, Gomel Oblast, located outside the 30-km zone and (2) Krasnopolye Raion, Mogilev Oblast. The values of K_j also depend on data relevant to those two reference areas.

RESULTS AND DISCUSSION

A list of the main activities conducted during the implementation of the initial assessment (also called first iteration) of thyroid dose reconstruction for the inhabitants of the Republic of Belarus is presented in Table 4. The results related to Class 1, Class 2, and Class 3 thyroid dose estimates are discussed in turn.

Estimation of Class 1 individual thyroid doses ("measured" doses)

Because of the use of different types of equipment, great care was needed to follow the measurement procedures correctly, including intercalibration of different types of equipment, decontamination of the subjects prior to measurement, etc. Unfortunately, it was difficult to provide adequate equipment and guidance to all of the radiation-monitoring teams operating in Belarus. Therefore, in order to prepare a reliable data bank of individual thyroid doses for Belarussian residents, a substantial effort was required to collect and analyze all available results.

Quality of the data was not uniform. A number of people, mainly from the more contaminated areas in the southern part of Gomel Oblast where thyroid measurements were carried out with greater intensity than anywhere else in Belarus, were measured up to 10–15 times at different locations and at different times. However, many people with possibly high thyroid exposures were not measured at all. The fraction of people without thyroid measurement is very high in areas with relatively high contamination located in the northeastern part of Gomel Oblast and in the southeastern part of Mogilev Oblast.

During the first stage of verification of collected data, almost all of the measurements made after 5 June 1986 were excluded because values of the exposure rates measured near the thyroid, $P_{th}(t_m)$, were essentially equal to background, $P_b(t_m)$. In addition, some of the measurements carried out before 5 June 1986 were excluded because they were suspected to represent only background measurements. The indication of such a situation was a small difference (much less than a geometric standard deviation of 1.8 to 2.0) between the values of $P_{th}(t_m)$ and $P_b(t_m)$ for any individual and the appropriate mean value for all individuals.

The approximately 130,000 results of thyroid measurements (Class 1 thyroid doses from ^{131}I) have been organized into a dosimetry data bank. The uncertainties in the thyroid dose estimates are assumed to be distributed according to a lognormal function with geometric standard deviation β. The value of β is mainly

Table 4. Description of activities carried out to implement the initial assessment of thyroid-dose reconstruction for the residents of Belarus.

Type of activity	Dates	Result
Monitoring ^{131}I content in the thyroids of Belarussian inhabitants	May–June 1986	More than 200,000 people were examined
Personal interviews of the population living in the contaminated areas	1988	About 150,000 results of personal interviews
Development of the methodology to estimate thyroid doses on the basis of results of *in vivo* thyroid measurements	1988–1989	Published reports: Gavrilin et al. (1989a,b)
Collection and analysis of the thyroid measurements; estimation of individual thyroid doses (Class-1)	1987–1991	Data bank containing measured thyroid doses for 130,000 inhabitants of Belarus
Estimation of the contribution of short-lived radioiodines and ^{132}Te to the internal thyroid exposure	1986–1991	Published report: Gavrilin et al. (1991b)
"Passportization" of the settlements of Belarus	1991–1992	Class-2 thyroid doses for unspecified individuals of over 800 villages in the Gomel and Mogilev Oblasts (Gavrilin et al. 1991a)
Collection and verification of environmental ^{131}I contamination data	1987–1993	Database containing the spectrometric results of measurements of soil, grass, and milk sampled in May–July 1986
Analysis of the relationship between the "measured" thyroid dose and the environmental contamination data	1990–1994	Semi-empirical formula allowing for the assessment of inferred thyroid doses (Class 3) on the basis of ^{137}Cs (^{131}I) ground-deposition density in the settlements

determined by three factors: (1) uncertainty in the estimate of the ^{131}I content in the thyroid, β_G; (2) uncertainty in the thyroid mass, β_m [β_m = 1.6 according to Dunning and Schwarz (1981)]; and (3) uncertainty in the dynamics of the ^{131}I intake, β_f. The value of β_f is estimated to be 1.3 (Gavrilin et al. 1996a). The approximately 130,000 results have been divided into three groups of reliability according to the value of β_G in each group (Table 5). The first group of reliability includes the results obtained by means of SRP-68-01 radiometers or by DRG3-02 exposure rate meters on people who had removed their contaminated clothes and had washed themselves prior to the thyroid measurement. Included in this group are the results related to individuals whose thyroids were measured several times in hospitals.

The second group of reliability consists of results obtained by means of DP-5 exposure rate meters at locations with low background levels, $P_b(t_m)$. As a rule, people had removed their contaminated clothing and had washed themselves before the measurements were made.

The third group of reliability contains data obtained using DP-5 exposure rate meters at locations with high background levels. As a rule, the individuals measured had neither removed their contaminated clothes nor washed themselves prior to the measurements (Gavrilin et al. 1992).

Table 5. Distribution of Class-1 thyroid-dose estimates according to three groups of reliability.

	Group of reliability		
	1	2	3
Value of geometric standard deviation, β_G	$\beta_G \leq 1.3$	$1.3 < \beta_G \leq 2.0$	$2.0 < \beta_G \leq 2.2$
Number of people	22,000	40,000	68,000
Percentage of people in the group	17	31	52

It should be stressed that the classification of the data presented in Table 5 is based mainly on the quality of the thyroid measurements; reevaluation of the classification of those data during the second assessment is planned.

For the first assessment of thyroid dose calculation, only a few answers to the personal interviews conducted in 1988 were used: Those related to the effective date when fresh milk consumption by the residents in the village was stopped and those related to the date of evacuation from the village (when appropriate). It is well known that milk is one of the main foodstuffs consumed in the rural areas of Belarus. The personal interviews revealed that the majority of people who lived in the contaminated areas continued to drink milk for some time after the accident. Thyroid doses for individuals in villages were calculated by assuming a single ^{131}I deposition in the areas considered and ^{131}I intake due to fresh milk consumption.

Individual thyroid doses to the residents with thyroid measurements of the cities of Gomel, Mogilev, and Mozyr were calculated as arithmetic means of two values. The first value is the dose estimate calculated with the assumption of ^{131}I intake due only to the consumption of milk resulting from a single occurrence of ^{131}I fallout in the vicinity of the city considered, while the second value is the dose estimate calculated as if inhalation of ^{131}I at the time of fallout were the only cause of internal irradiation.

A large number of thyroid measurements was made on residents of Minsk who stayed in the city in

April–May 1986. These measurements were used to derive the variation of the mean value of ^{131}I content in the thyroid as a function of time after the accident. This temporal variation, which was approximated as the sum of two exponential functions, was used to calculate the thyroid doses for the Minsk residents who did not leave the city (Gavrilin et al. 1993). However, individual thyroid doses to the residents of Minsk who left the city and lived in April–May 1986 in contaminated areas were calculated according to the models used for the inhabitants of these areas. Residents of Minsk with anomalously high ^{131}I thyroid content and without information on their whereabouts in April–May 1986 were classified into special subgroups.

Table 6 presents the geographical distribution of the "measured" thyroid dose estimates (Class 1) for the approximately 130,000 Belarussian people included in the dosimetry data bank, which is kept at the Institute of Biophysics in Moscow, with a copy at the Institute of Radiation Medicine in Minsk. In general, three estimates of individual thyroid dose are provided in the dosimetry data bank: The basic value calculated using the appropriate ^{131}I intake, an estimate of the upper bound (97.5 percentile), and an estimate of the lower bound (2.5 percentile) associated with the basic value.

Examples of the cumulative frequency of individual thyroid dose distributions for adults in several villages are presented in Fig. 2. These examples show that the individual thyroid dose distribution can be approximated satisfactorily by a lognormal function, especially for Pogonnoe. The deviation of the left part of the dose distribution from the straight line for villages other than Pogonnoe can be explained by different reasons. It is, for example, possible that the values of the background, $P_b(t_m)$, were overestimated. In that case, a numerical method could be used to determine the optimum value of systematic bias of $P_b(t_m)$ and then to estimate the parameters of the refined individual thyroid dose distribution. Other explanations can also be invoked. For instance, there could have been groups of inhabitants in the villages considered who did not drink milk at all. This problem has not been taken into consideration during the initial assessment of thyroid dose reconstruction.

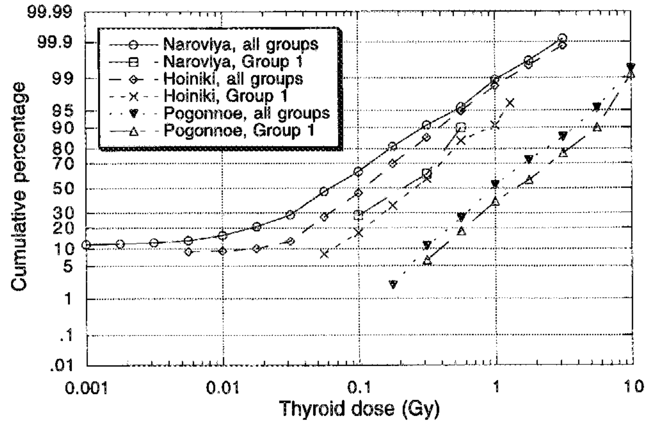

Fig. 2. Cumulative percentage of Class 1 individual thyroid doses from ^{131}I for adults in three locations. Separate results are given for individuals in the highest group of reliability (Group 1) and for all groups of reliability.

The characteristics of the individual thyroid dose distributions obtained for children up to 18 y of a number of regions and cities are presented in Table 7. Geometric means, geometric standard deviations, 10th percentiles, 90th percentiles, and maximum values of individual thyroid dose are indicated. In each of the areas considered there is a wide variability in the estimates of individual thyroid doses. This variability is due to a number of factors, among which are the heterogeneity of the ^{131}I ground deposition densities, the variability in the ^{131}I concentrations in milk, the variability in the milk consumption rates and the metabolism of the individuals,

Table 6. Characteristics of the data bank of individual thyroid dose estimates as of 1997.

	Number of inhabitants with different classes of dose estimates (thousands) with percentage of the population in parentheses					
	Children			Adults		
Territories	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Three raions of Gomel Oblast: Hoiniki, Bragin, and Narovlya	17.5 (61%)	7 (25%)	4 (14%)	48.8 (59%)	21 (26%)	13 (15%)
Five raions of Gomel Oblast: Vetka, Buda-Koshelev, Korma, Rechitsa, and Loev	7.2 (11%)	10 (15%)	50 (74%)	11.6 (6%)	45 (23%)	140 (71%)
Five raions of Mogilev Oblast: Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod	4.4 (12%)	15 (41%)	17 (47%)	8.5 (8%)	35 (33%)	61 (59%)
Minsk City	7.2 (2%)	380 (98%)	—	12.8 (1%)	1110 (99%)	—
Gomel, Mogilev, and Mozyr Cities	3.2 (1%)	235 (99%)	—	5.1 (1%)	680 (99%)	—
Remaining territory of Belarus	—	—	≈1730 (100%)	—	—	≈5240 (100%)
Total	39.5 (2%)	650 (25%)	≈1880 (73%)	86.8 (1%)	≈1890 (25%)	≈5450 (74%)

Table 7. Estimated Class-1 thyroid doses from ^{131}I for children aged 0 to 18 y at the time of the accident in some areas of Belarus.

Areas	Number of children	10th percentile of dose (Gy)	Geometric mean dose (Gy)	90th percentile of dose (Gy)	Maximum dose (Gy)	GSD[a]
Evacuated villages (before 5 May 1986) in Bragin, Hoiniki, and Narovlya Raions	1,645	0.18	1.3	5.4	50	3.0
Non-evacuated villages in Bragin, Hoiniki, and Narovlya Raions	9,704	0.08	0.5	2.4	57	3.3
Villages in the northeastern raions of Gomel Oblast	1,962	0.05	0.28	1.5	20	3.5
Rechitsa and Loev Raions	5,293	0.038	0.36	1.8	25	3.3
Gomel City	836	0.041	0.13	0.56	7.5	3.3
Five raions of Mogilev Oblast (Chericov, Klimovichi, Kostukovichi, Krasnopolye, and Slavgorod)	4,486	0.007	0.15	0.7	20	3.3
Minsk City, children who lived in the city April–May 1986	6,360	0.003	0.031	0.14	1.2	3.1
Minsk City, children who left the city and lived in villages in contaminated areas April–May 1986	920	0.027	0.34	1.5	11	3.0

[a] Geometric standard deviation.

and the uncertainties associated with the thyroid measurements.

Estimation of Class 2 thyroid doses (doses "derived by affinity")

The thyroid dose estimates provided using the Class 2 methodology are illustrated in Table 8 for a village in Gomel Oblast. Estimates are given for an array of age classes and of milk consumption rates. The thyroid dose corresponding to a specified individual is read in the Table according to the age of the individual considered and his or her milk consumption rate, in the usual case when that individual stayed in the same village during a few weeks after the accident and did not interrupt his or her consumption of local milk during that period of time. If that is not the case, simple corrections are made to take those changes into account.

Table 8. Examples of Class-2 thyroid doses resulting from inhalation and ingestion of radioiodines (^{131}I to ^{135}I) and of ^{132}Te. The estimated thyroid doses and their associated uncertainties (geometric standard deviations, GSD) are for the population of the village Dronki in the raion of Hoiniki of Gomel Oblast.[a]

Inhalation only			Milk consumption rate (L d^{-1})									
			0.1		0.3		1.0		4.0		unknown	
Age (y)	Dose (Gy)	GSD	Dose (Gy)	GSD	Dose (Gy)	GSD	Dose (Gy)	GSD	Dose (Gy)	GSD	Dose (Gy)	GSD
0–1	0.09	2.9	1.0	2.4	2.5	2.5	8	2.6	30	2.6	3	2.8
1–2	0.09	2.9	0.8	2.4	2.0	2.5	7	2.5	25	2.6	3	2.8
2–3	0.09	2.9	0.7	2.3	1.5	2.5	5	2.5	20	2.6	2.0	2.8
3–4	0.09	2.9	0.6	2.3	1.5	2.5	5	2.5	20	2.6	2.0	2.8
4–5	0.09	2.9	0.5	2.3	1.5	2.4	4	2.5	15	2.6	1.5	2.8
5–6	0.09	2.9	0.5	2.3	1.0	2.4	3	2.5	15	2.6	1.5	2.8
6–7	0.09	2.9	0.4	2.2	1.0	2.4	3	2.5	10	2.6	1.5	2.7
7–8	0.09	2.9	0.4	2.2	0.9	2.4	2.5	2.5	10	2.6	1.0	2.7
8–9	0.09	2.9	0.4	2.2	0.8	2.4	2.5	2.5	9	2.6	1.0	2.7
9–10	0.09	2.9	0.3	2.2	0.8	2.4	2.0	2.5	8	2.6	1.0	2.7
10–11	0.09	2.9	0.3	2.2	0.7	2.4	2.0	2.5	7	2.6	0.9	2.7
11–12	0.09	2.9	0.3	2.2	0.7	2.3	2.0	2.5	7	2.6	0.8	2.7
12–13	0.09	2.9	0.3	2.2	0.6	2.3	1.5	2.5	6	2.5	0.8	2.7
13–14	0.09	2.9	0.3	2.2	0.6	2.3	1.5	2.5	6	2.5	0.9	2.7
14–15	0.09	2.9	0.25	2.2	0.6	2.3	1.5	2.5	6	2.5	0.8	2.7
15–16	0.09	2.9	0.25	2.2	0.5	2.3	1.5	2.5	5	2.5	0.8	2.7
16–17	0.09	2.9	0.25	2.2	0.5	2.3	1.5	2.5	5	2.5	1.0	2.7
17–18	0.09	2.9	0.25	2.2	0.5	2.3	1.5	2.5	5	2.5	0.9	2.7
>18	0.08	2.9	0.20	2.2	0.4	2.0	1.0	2.1	4	2.2	0.8	2.4

[a] The following assumptions have been made: (1) The effective date of local contamination was 27 April 1986 and (2) the last day of consumption of contaminated milk was the day of evacuation: 3 May 1986 for children up to 18 y and 4 May 1986 for adults.

As shown in Table 8, 19 age classes are considered: Children year by year until 18 y of age and one class for adults. The milk consumption rates range from 0.1 to 4.0 L d^{-1} (only a few values are presented in Table 8); in addition, a default value is used when the milk consumption rate is unknown. The dose estimates are the sum of the contributions from inhalation and from ingestion. The uncertainties attached to the thyroid dose estimates also are provided in terms of geometric standard deviations.

At present, Class 2 thyroid dose estimates are available for residents of over 800 rural villages of 13 raions of the Gomel and Mogilev Oblasts, as well as for the cities of Minsk, Mozyr, Gomel, and Mogilev. The locations of these 13 raions and four cities are noted in Fig. 3. For each location, data concerning the number of children with Class 1 and Class 2 thyroid dose estimates are presented in Table 9; the total number of 0 to 18-y-old children with Class 2 doses is about 760,000. The arithmetic mean thyroid doses for each location and two age categories of children are given in Table 10. Among the young children (0 to 6 y old), the average Class 2 thyroid dose estimates range from 0.08 Gy in the city of Minsk to 4.7 Gy for the non-evacuated children of Hoiniki raion.

Estimation of Class 3 thyroid doses ("empirically-derived" doses)

Class 3 thyroid doses are only estimated when the number of thyroid measurements in a village or city is not sufficient to derive Class 2 estimates with reliability.

The determination of Class 3 doses is based on analysis of the relationship between the ^{137}Cs deposition density in a locality and the mean Class 1 thyroid doses for the adult population of that locality, normalized to the

Fig. 3. Map of the southern part of Belarus with identification of the cities and raions where Class 2 thyroid doses have been estimated. Information on the settlements with estimated Class 2 thyroid doses is provided in Table 9, while numerical dose values are given in Table 10.

^{137}Cs deposition density. The dots in Fig. 4 show the values obtained for a number of such localities, while the solid curve is the result of the model described by eqn (8). The apparently surprising result that the doses are not proportional to the ^{137}Cs deposition densities may be partly explained by the fact that the high ^{137}Cs deposition densities are generally associated with precipitation. This results in a retention of radionuclides by vegetation that is lower than when deposition occurs in the absence of precipitation, which is generally associated with low ^{137}Cs deposition densities. Consequently, the ingestion intakes of ^{131}I with contaminated milk as well as the thyroid doses due to ingestion are roughly independent of the deposition density.

As ^{137}Cs deposition densities are available for the entire territory of Belarus, Class 3 thyroid dose estimates can be obtained for the populations of any locality of Belarus. In this way, a collective thyroid dose of about 500,000 person-Gy resulting from the intake of ^{131}I has been roughly estimated for the entire population of Belarus (Gavrilin et al. 1996a).

FUTURE WORK

The work described above concerns the preliminary assessment of thyroid doses (first iteration) for the populations of Belarus that were affected by the Chernobyl accident. Efforts are now underway to refine these thyroid dose estimates in a second iteration and to quantitatively assess the appropriate dose uncertainties.

The following tasks are under consideration or have been undertaken:

1. Quantitative description of the main factors that affected the results of the ^{131}I thyroid content determination while the thyroid was being measured (Class 1 doses);
2. Verification of the results of personal interviews, which were conducted in 1988 (Class 1 and Class 2 doses); and
3. Development of an algorithm describing the kinetics of intake of ^{131}I and of other radionuclides of iodine and tellurium by Belarussian inhabitants who lived in different areas. Improvement of the methodology used to estimate the relative contributions of inhalation and ingestion to the thyroid dose on the basis of results of personal interviews regarding level of milk consumption, potassium iodide intake, and other relevant information (Class 1 doses).

The decision to accept the model of a single ^{131}I deposition in the contaminated areas of Belarus will be re-evaluated for the second iteration. Experimental data on ^{131}I daily deposition density, measured by the Scientific Production Association "Taifun,"†† are available for seven cities: Baranovichi, Brest, Gomel, Grodno, Minsk, Mogilev, and Vitebsk (Makhon'ko et al. 1996). Fig. 5 presents such results for Gomel,

†† Scientific Production Association "Taifun," Obninsk, Kaluga Oblast, Russia, personal communication, 1995.

Table 9. Data concerning the number of measured thyroid doses keyed according to the locations indicated in Fig. 3.

Key to Fig. 3	Location	Number of passportized villages or cities	Number of reliably passportized villages or cities	Number of 0–18-year-old children	Number of children with measured doses	Percentage of children with measured doses
1	Minsk City	1	1	390,000	7280	2
2	Mozyr City	1	1	25,000	710	3
3	Narovlya Raion	72	47	7,000	3080	44
4	Hoiniki Raion	91	76	11,600	8130	70
5	Bragin Raion	135	116	10,000	7080	71
6	Loev Raion	85	27	5,200	2480	48
7	Rechitsa Raion	66	22	33,000	2810	9
8	Gomel City	1	1	123,000	2260	2
9	Buda-Koshelev Raion	83	2	13,000	240	2
10	Vetka Raion	61	14	10,000	1320	13
11	Korma Raion	44	6	6,800	400	6
12	Slavgorod Raion	62	13	6,000	1000	16
13	Krasnopolye Raion	73	31	5,700	1070	19
14	Kostukovichi Raion	52	23	8,900	1190	13
15	Chericov Raion	27	17	5,800	940	16
16	Klimovichi Raion	35	10	9,800	280	3
17	Mogilev City	1	1	90,000	200	0.2
	Total or average	890	408	760,800	40,740	5

Table 10. Estimates of arithmetic mean-thyroid doses for the residents of the cities and raions identified in Fig. 4.

Key	Location	Arithmetic mean-thyroid dose (Gy) for age group		
		0–6 y	7–17 y	Adult
1	Minsk City	0.08	0.029	0.018
2	Mozyr City	0.21	0.14	0.10
3	Narovlya Raion	1.34[a]	0.70[a]	0.36[a]
		1.55[b]	0.57[b]	0.45[b]
4	Hoiniki Raion	1.6[a]	0.60[a]	0.47[a]
		4.7[b]	2.1[b]	1.6[b]
5	Bragin Raion	1.7[a]	0.52[a]	0.48[a]
		2.1[b]	1.1[b]	0.80[b]
6	Loev Raion	0.5	0.18	0.12
7	Rechitsa Raion	0.4	0.14	0.11
8	Gomel City	0.46	0.18	0.078
9	Buda-Koshelev Raion	0.38	0.30	0.11
10	Vetka Raion	1.6	0.94	0.34
11	Korma Raion	0.23	0.16	0.06
12	Slavgorod Raion	0.22	0.11	0.095
13	Krasnopolye Raion	0.62	0.29	0.19
14	Kostukovichi Raion	0.45	0.29	0.21
15	Cherikov Raion	0.54	0.21	0.13
16	Klimovichi Raion	0.36	0.18	0.088
17	Mogilev City	0.16	0.076	0.043

[a] Outside the 30-km zone of the Chernobyl Plant.
[b] Inside the 30-km zone.

Brest, and Vitebsk. This time course of behavior is typical of data on ^{131}I daily deposition density available for Belarussian locations.

The available environmental radiation measurements carried out early after the accident will also be reviewed in order to check the consistency of Class 1 dose estimates with the results of those measurements. In May–July 1986, before ^{131}I decayed to negligible levels, environmental samples were taken in Belarus and analyzed for ^{131}I and other radionuclides. Two sets of such data are available at the Institute of Biophysics in Moscow: One obtained from the Institute of Nuclear Energy, Minsk (Dubina et al. 1990) and the other related to environmental samples taken during the expedition of the Institute of Biophysics in the Gomel Oblast in May–June 1986;[‡‡]

4. Substantiation of the choice of distribution function of true individual thyroid dose values taking into account the peculiarities of thyroid dose accumulation in the villages (Class 2 doses);

[‡‡] F. Levochkin, V. Gusykov, A. Titov, S. Panchenko et al., Institute of Biophysics, Moscow, personal communication, 1990.

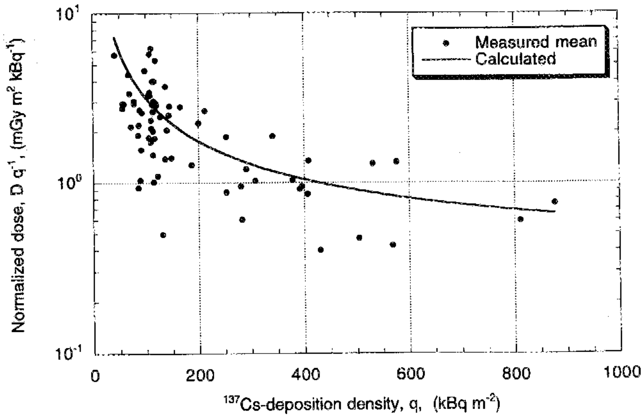

Fig. 4. Thyroid doses normalized to the ^{137}Cs deposition density: The dots represent arithmetic means of the Class 1 thyroid doses for the adult populations in each settlement, while the solid curve was calculated from eqn (8).

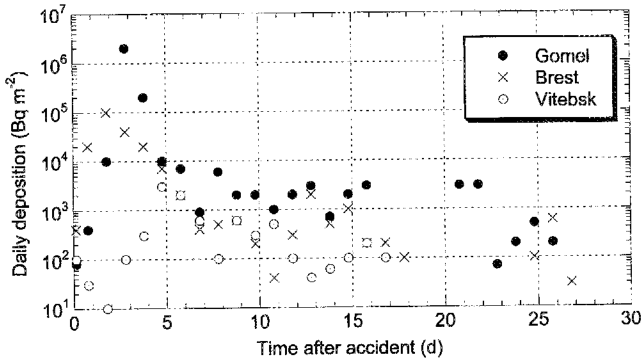

Fig. 5. Measured daily deposition of ^{131}I in the cities of Gomel, Brest and Vitebsk (Makhon'ko et al. 1996). Each collector of fallout deposition was exposed during a 24-h period beginning at 8:00 a.m. local time.

5. Development of a method of Class 3 thyroid dose reconstruction based on measurements of the deposition density of ^{129}I (half-life of 1.6×10^7 y).

In a first step of the implementation of Class 3 thyroid dose reconstruction on the basis of ^{129}I activity measurements in soil, undisturbed soil was sampled in eleven villages in May 1993. The selection of these villages was based on the availability of Class 1 thyroid dose estimates, as well as of spectrometric results of ^{131}I and ^{137}Cs activity in soil and grass samples made during the very first weeks after the accident. The villages were also selected with substantially different values of ratios of ^{131}I:^{137}Cs ground deposition densities in order to analyze the relationship of the ^{129}I concentrations in soil with those of ^{131}I and ^{137}Cs. The results obtained (Straume et al. 1996) seem to indicate that the knowledge of ^{129}I deposition density would lead to an improvement in the estimation of the Class 3 thyroid doses in areas where information on the ^{131}I ground deposition density is missing; and

6. Separate description of systematic and random errors attached to the dose uncertainties (Class 1, Class 2, and Class 3 doses).

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